Method and Circuit System for Calibrating Voltage and Temperature Deviations of the Effective Current of Hydraulic Valves in a PWM Drive

The present invention relates to a method and a circuit arrangement for calibrating voltage and temperature deviations of the effective current of hydraulic valves in a PWM control according to the preambles of claims 1 and 11.

It is known that significant differences between the regulated nominal current and the effective current occur in the coil in a valve actuation by means of a pulse-width-modulated current (PWM current control), at least when the ratio between PWM frequency and the time constant of the coil is unfavorable. It is further known in the art that there are dependencies on external parameters such as supply voltage and temperature.

For example, the (maximum possible) current

$$I_{100\%} = V_{REFx}/(R_L + R_{DSon-LS}).\qquad(1)$$

flows through a permanently activated inductive load (e.g. valve coil).

This current consequently depends on

- the voltage at the top side of the valve, and, thus, indirectly, on the battery voltage available in the motor vehicle at terminal KL30B,
- on the coil resistor R_L and (to a lower degree) on the on-

resistor $R_{DSon-LS}$ of the semiconductor element(s) used to actuate the load(s). Both resistors are highly temperature-responsive: variations of approximately 0.4 % per 1 °C for the load resistor (this is e.g. the temperature coefficient for copper, real coils have a somewhat lower dependency) und 0.5 % per 1 °C for $R_{DSon-LS}$ (e.g. Power-MOSFETs, provided on one chip) are typical values.

An object of the invention is to disclose a method and a circuit arrangement for driving loads, reducing deviations from the nominal current and the effective current that flows in the load.

This object is achieved according to the method as disclosed in claim 1 and the circuit arrangement as claimed in claims 11 and 12.

A compensation variable according to the invention implies a compensating current ΔI, which can adopt both positive and negative numerical values.

In the method of the invention for reducing deviations between the effective current I_{RMS} and the measured current I_{meas} in a pulse-width-modulated current control, it is preferred to determine the measured current I_{meas} in the middle of the switching time t_{on} during an actuation period t_{PWM}.

In a preferred manner, the supply voltage dependency is compensated by the extraction of a valve-related table from defined discrete reference points, wherein the discrete reference points are especially favorably formed of pairs of values produced from the nominal current $I_{nominal}$ and the supply voltage V_{KL30B}. Further, it is preferred that values lying between the discrete reference points are determined by

interpolation.

Favorably, the valve-related table is stored in a data memory that is preferably a non-volatile data memory in which data is preserved even after the ignition's switch-off.

It is preferred that the compensation variables are determined separately for each load, in particular for each valve coil, or stored in a table.

Further preferred embodiments can be taken from the sub claims and the following description of an embodiment by way of Figures.

In the drawings,

Figure 1   exhibits the difference between the current measurement in PWM actuation and the average current and the effective current.

Figure 2   shows the difference between the measured current and the effective current for a typical hydraulic valve.

Figure 3   shows the difference between the measured current and the effective current for a typical hydraulic valve relative to the difference that prevails with a supply voltage of 12 volt and at a temperature of 25 °C.

The current variation at a valve coil is plotted as a function of time t in Figure 1. With a current control by means of PWM actuation, an average current of

$$I_{AVG} = DC * I_{100\%} = DC * V_{REFx} / (R_L + R_{DSon-LS}) \qquad (2)$$

develops, with *DC* indicating the pulse-duty factor (*Duty Cycle*) of the PWM actuation. The mode of operation of a PWM control that can be implemented according to the invention has been disclosed in international patent application PC/EP 0 115 040. Strictly speaking, equality applies only with an actuation by means of straight line 1 or with ideal e-functions.

For current control, it is necessary to measure the present coil current at a defined time, illustrated by the symbol @ ("at"), e.g. after half the switching time t_{on}. Consequently, the controller adjusts a measured current I_{meas} of

$$I_{meas} = I(@\ t_{on}/2) = I_{nominal} \qquad (3).$$

The measured current I_{meas} corresponds to the average current I_{AVG} only when actuation takes place by way of straight lines. With an actuation with ideal e-functions (corresponds to a coil without an iron core), the current I_{meas} measured at time $t_{on}/2$ is higher that the average current I_{AVG}. In current control of a valve, however, the effective current I_{RMS} is of interest that is still somewhat lower than the average current I_{AVG}. Saturation effects (hysteresis) will additionally be encountered in a valve that can be illustrated in a simplified manner as a coil with an iron core, with the result that non-linearities occur, as becomes apparent from the variation of the current curve 2. From this results a further deviation between the effective current I_{RMS} and the measured current I_{meas}. Thus,

$$I_{nominal} = I_{AVG} = DC * V_{REFx}/(R_L + R_{DSon-LS}) \qquad (4)$$

applies in approximation. This equation is the more precise the higher the PWM frequency is.

Figure 2 shows the difference between the measured current I_{meas} and the effective current I_{RMS} for the electromagnetic valve of an electronic brake control unit, plotted by way of the nominal current $I_{nominal}$, for different voltages at KL30B and different coil temperatures. The difference decreases with a rising nominal current $I_{nominal}$: This results from the fact that the current controller starts reaching saturation (that means the *Duty Cycle* amounts to 100 % approximately).

A first compensation is still relatively simple in order to eliminate the dependency on the nominal current $I_{nominal}$. A current difference to be taken from the diagram is added for a defined nominal current $I_{nominal}$. This is successful only for a defined voltage and a defined temperature. Example: nominal value compensation at V_{KL30B} = 12 volt and T = 25 °C (curve 3). To reach an effective current I_{RMS} = 1 A, a nominal current $I_{nominal}$ = 1 A + 62.5 mA is predetermined.

Figure 3: To detect voltage and temperature dependencies, it is appropriate to illustrate the deviations of the curves of Figure 2 from a reference curve (at V_{KL30B} = 12 volt and T = 25 °C) (see illustration 3). It can be seen that e.g. at a nominal current $I_{nominal}$ = 1.1 A, there is a maximum voltage dependency of -37.5 mA / +29 mA at a voltage ranging from 9 volt to 16.5 volt approximately over a constant temperature of 25 °C. On the other hand, with a temperature variation of roughly -40 °C to roughly 180 °C with respect to a constant voltage of 12 volt, it is possible to read a maximum temperature dependency of +10.5 mA/-25.5 mA with a nominal current $I_{nominal}$ = 1.1 A. These two dependencies do not add simply linearly because in the two corner points {17 volt, -40 °C} and {9 volt, 180 °C} only deviations of +30.5 mA/-49.5 mA are reached for 1.1 A. However, the influence of the voltage

is significantly greater than the influence of the temperature.

A (valve-related) table is produced for a compensation of the voltage dependency in Figure 3. Defined discrete reference points are used for this purpose, which respectively comprise a pair of values {$I_{nominal}$, V_{KL30B}}, and one compensation current ΔI is stored with respect to each pair of values {$I_{nominal}$, V_{KL30B}} for the adaptation of nominal values. Intermediate values are determined by means of interpolation. For example, it is desired to achieve an increase of the nominal current $I_{nominal}$ of 200 mA to 1000 mA at a voltage of 9 volt at the valve and a temperature of 180° C, corresponding to curve 19 in Figure 3. To achieve the nominal current $I_{nominal}$ = 1000 mA, a compensating current ΔI = -45 mA is added to the nominal current $I_{nominal}$ = 1000 mA. However, as the valve, due to its time constant, follows the specification of the nominal current with delay, initially only a compensating current ΔI = -10 mA is predetermined for compensation. This corresponds to the current compensation at $I_{nominal}$ = 200 mA. The current variation at the valve is thereby adapted to the variation of the curve 19. Further, the compensating current ΔI is adjusted corresponding to the course of the curve 19 until the nominal current $I_{nominal}$ = 1000 mA is reached.

To compensate variations or abrupt changes in the supply voltage (e.g. at KL30B), an averaging operation by way of the present voltage measurement and previous values is preferred.

For the compensation of the temperature dependency, the temperature is indirectly detected by way of the *Duty Cycle* adjusted by current control. From equation (4),

$$R_L + R_{DSon-LS} = (DC * V_{REFx})/I_{nominal} \tag{5}$$

follows. This formula implies that for the present *Duty Cycle* only the coil resistor R_L (and the *on*-resistor $R_{DSon-LS}$) is responsible; the coil temperature appears only indirectly. Therefore, it is initially suitable to convert the data in illustration 3 to a dependency of the coil resistor R_L (and the *on*-resistor $R_{DSon-LS}$):

$$R_L(T) = R_L(@ T_{reference}) * (1 + \alpha_{coil} * (T_{present} - T_{reference})) \text{ or}$$

$$R_{DSon-LS}(T) = R_{DSon-LS}(@T_{reference}) * (1 + \alpha_{Ron} * (T_{present} - T_{reference})). \quad (6)$$

In equation (6), the temperature-responsive values of the coil resistor $R_L(T)$ and the *on*-resistor $R_{DSon-LS}(T)$ are determined in consideration of known resistor values $R_L(@T_{reference})$, $R_{DSon-LS}(@T_{reference})$ at a reference temperature $T_{reference}$. To this end, the known resistor values $R_L(@T_{reference})$, $R_{DSon-LS}(@T_{reference})$ are multiplied with coefficients of correction. These coefficients of correction are basically composed of temperature coefficients (α_{coil}, α_{Ron}) and a temperature difference between the present temperature $T_{present}$, which is determined from the present *Duty Cycle*, and the reference temperature $T_{reference}$. In this respect, α_{coil} describes the temperature dependency of the coil material used and α_{Ron} describes the temperature dependency of the *on*-resistor $R_{DSon-LS}$. The *on*-resistor $R_{DSon-LS}$ represents the parasitic resistance of a switch, with said switch being realized in the shape of a MOSFET-transistor provided on a semiconductor chip. It is also possible to achieve this required switching function in another way, i.e. by means of relay technology, bipolar technology, etc. To relate the dependency to $R_L + R_{DSon-LS}$ rather than to the temperature offers the additional advantage that different temperatures in the valve and in the semiconductor chip are detected correctly because these different temperatures are implicitly contained in the present *Duty Cycle*.

Each one ΔI is in turn stored for pairs of values $\{I_{nominal}, R_L + R_{DSon-LS}\}$ in a table for the purpose of adaptation of nominal values. An additional calibration is suitable in this respect because equation (4) applies only in approximation. It is advisable to measure the *Duty Cycle* with a specific valve and reference values (e.g. $I_{nominal} = 1$ A, temp. $= 25$ °C, $V_{KL30B} = 12$ volt) and to convert the table by means of a corresponding offset.